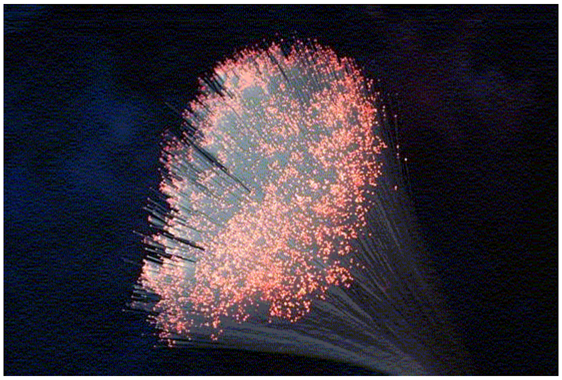
Splices, Connectors, and Fiber Optic Components



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Splices, Connectors, and Fiber Optic Components

- **Fiber cable lengths are limited**
- **How do we join fibers?**
  - **Splices**
  - **Connectors**
- **Can we divide the power in a fiber?**
  - **Ex., 1 fiber in; 2 fibers out**
- **How can we isolate a laser source from back reflections?**
- **Can we make optical filters out of fibers (i.e., ready to splice into fiber links)?**

Splice-2

Fiber Joints

- **Joints**
  - **Interconnect fiber lengths**
    - **Available up to few kilometers**
  - **Connect source/detector pigtails to fiber**
  - **Pass through bulkheads, walls, etc.**
- **Want...**
  - **Low insertion loss**
  - **High strength**
  - **Simple installation**
- **Two types of joints**
  - ***Splice*: permanent joint**
  - ***Connector*: temporary joint**

Splice-3

Connectors and Splices: Joining Losses

- **Causes of loss**
  - ***Intrinsic losses:*** **Depend on fiber properties**
  - ***Extrinsic losses:*** **Losses due to external factors (e.g., fiber misalignment)**
  - **In general, <u>not</u> same in both directions**
- ***(Transmission) joint loss*** **[dB]**

$$\boxed{L_j\,[\mathrm{dB}] = -10\log\left(P_{\mathrm{out}}/P_{\mathrm{in}}\right) = -10\log(\eta)}$$

- η **is "coupling efficiency"**

Splice-4

Fiber Parameter Effects: Multimode Fibers

- **Coupled optical power depends on number of modes in each fiber**
  - **Number of modes:**

$$N = k^2 \int_0^a \mathrm{NA}^2(r)\, r\, dr = k^2 \mathrm{NA}^2(0) \int_0^a \left[1 - (r/a)^g\right] r\, dr$$

  - **Optimum coupling when number of modes is matched**
  - **Loss factors**
    - **Core radius *a*, *n*umerical aperture NA(0), index gradient *g***
  - **Isolate effects as if independent and add dB losses**
- **Losses also depend on mode *power distribution***
  - **Assume uniform distribution**
  - **Reality: uneven distribution due to launch conditions or mode coupling effects**
  - **Measurements need to be made with all modes equally excited**

Fiber Parameter Effects: Multimode Fibers (cont.)

- **Effects of joining mismatched fibers**

1. NA effects:

$$L_{NA}[\mathrm{dB}] = \begin{cases} -10\log\left(\dfrac{\mathrm{NA_r}(0)}{\mathrm{NA_e}(0)}\right)^2 & \mathrm{NA_r}(0) < \mathrm{NA_e}(0) \\ 0 & \mathrm{NA_r}(0) > \mathrm{NA_e}(0) \end{cases}$$

$NA_r(0)$ [$NA_e(0)$] is NA of receiving [emitting] fiber

2. Fiber radius effects:

$$L_r[\mathrm{dB}] = \begin{cases} -10\log\left(\dfrac{a_r}{a_e}\right)^2 & a_r < a_e \\ 0 & a_r > a_e \end{cases}$$

3. Index profile effects:

$$L_g = \begin{cases} -10\log\left(\dfrac{g_r(g_e+2)}{g_e(g_r+2)}\right) & g_r < g_e \\ 0 & g_r > g_e \end{cases}$$

Combined effects:

$$L_{\mathrm{Total}}(\mathrm{dB}) = L_{\mathrm{NA}} + L_r + L_g$$

Splice-6

- E.g., Coupling 50/125 SI (emitting) fiber with NA of 0.15 to 62.5/125 GI (g = 2) receiving fiber with NA =0.20 gives η = 0.5 (3 dB)

Fiber Parameter Effects: Multimode Fibers (cont.)

- **Loss is also function of...**
  - **Quality control of fiber fabrication**
    - » **Ellipticity of core**
    - » **Variations in *n(r)***
    - » **Core concentricity within cladding**
    - » **Variation in core diameter**
    - » **Other factors that depend on fabrication tolerances**
  - **Dominant effects: core diameter and NA**
  - **Lesser effect: core ellipticity and *n(r)***
- **User has little control over these factors**
  - **Specify tolerances**
  - **Establish acceptance screening procedures**

Splices and Connectors: Misalignment Effects

- ***Extrinsic* effects**
  - **Under control of connector/splice designer and user**
- **Primarily due to misalignment of fibers**
- **Determine required mechanical tolerances to meet given loss allocation**
- **In analysis of misalignments, usual assumptions are…**
  - **Fibers have equal radii, index profiles, and NAs to isolate misalignment effects**
  - **Power is uniform distribution across core area**

Splice-8

Connectors and Splices: Lateral Displacement Effects

- **Losses due to lateral fiber offset**

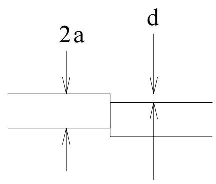


Fig. 4.2a
p. 99

SI fiber:

$$L_{\text{SI lateral}} = -10\log\left(\frac{2}{\pi}\cos^{-1}\left(\frac{d}{2a}\right) - \frac{d}{\pi a}\sqrt{1-\left(\frac{d}{2a}\right)^2}\right)$$

(Calculation of overlapping circular areas, centers separated by *d*)

- **GI fiber:**

$$L_{\text{GI latral}}[\text{dB}] \approx -10\log\left(1-\frac{8d}{3\pi a}\right) \quad \text{or}$$

$$L_{\text{GI lateral}}[\text{dB}] \approx -10\log\left(1-\left(\frac{2d}{\pi a}\right)\left(\frac{g+2}{g+1}\right)\right)$$

Splice-9

Connectors and Splices:
Longitudinal Displacement Effects

- **Losses due to longitudinal displacement**

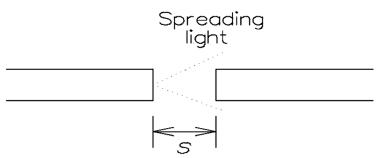


Fig. 4.2b
p. 99

- **Some light has spread beyond the area of receiving fiber core**

- **SI fiber:**

$$L_{\text{SI long}}[\text{dB}] = -10\log\left(\left(\frac{1}{1+\frac{s}{a}\tan\theta_{\max}}\right)^2\right)$$

$$= -20\log\left(\frac{1}{1+\frac{s}{a}\tan\theta_{\max}}\right)$$

($\theta_{\max}$: maximum acceptance angle = $\sin^{-1}$ NA)

Or

$$L_{\text{SI long}}[\text{dB}] \approx -10\log\left(1-\frac{s\sqrt{2\Delta}}{4a}\right)$$

- **GI fiber: No similar formula available (?)**

Connectors and Splices: Angular Misalignment

- **Losses due to angular misalignment**

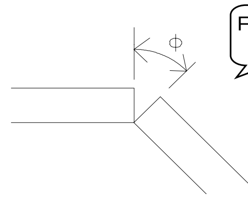


Fig. 4.2c
p. 99

- **GI and SI fiber:**

$$L_{\text{MM angular}}\left[\text{dB}\right] \approx -10\log\left(\left(1+\frac{\sin\phi}{\sqrt{2\pi\Delta}}\left(\frac{\Gamma\left(\frac{2}{g}+2\right)}{\Gamma\left(\frac{2}{g}+\frac{3}{2}\right)}\right)\right)^{-1}\right) = +10\log\left(1+\frac{\sin\phi}{\sqrt{2\pi\Delta}}\left(\frac{\Gamma\left(\frac{2}{g}+2\right)}{\Gamma\left(\frac{2}{g}+\frac{3}{2}\right)}\right)\right)$$

Γ**(x) is Gamma function**

$$L_{\text{MM SI angular}}\left[\text{dB}\right] \approx -10\log\left(\cos\phi\left\{\frac{1}{2}-\frac{1}{\pi}p\sqrt{1-p^2}-\frac{1}{\pi}\sin^{-1}p-q\left[\frac{1}{\pi}y\sqrt{1-y^2}+\frac{1}{\pi}\sin^{-1}y+\frac{1}{2}\right]\right\}\right)$$

$$\text{p}=\frac{\cos\theta_{\max}\left(1-\cos\phi\right)}{\sin\theta_{\max}\sin\phi},\quad \text{q}=\frac{\cos^3\theta_{\max}}{\left(\cos^2\theta_{\max}-\sin^2\phi\right)^{3/2}},\quad \text{y}=\frac{\cos^2\theta_{\max}\left(1-\cos\phi\right)-\sin^2\phi}{\sin\theta_{\max}\cos\theta_{\max}\sin\phi}$$

Splice-11

Splices and Connectors: Reflection Losses

- *(Fresnel)* ***reflection loss***
  - Coupling efficiency at perpendicular interface is

$$L_{\text{reflection}}\,[\text{dB}] = -10\log\left(\frac{P_{\text{transmitted}}}{P_{\text{incident}}}\right) = -10\log\left(1-\left(\frac{n-n_0}{n+n_0}\right)^2\right)$$

  - Reflection losses same regardless of direction of travel
  - Losses at air-glass interface: 0.2 dB each fiber face
  - Eliminate by…
    - » Use of index-matching gel or epoxy between fiber ends
    - » Physical contact of fiber ends ("PC" connection)
    - » Angled fiber ends (~8°)
    - » Using optical isolators
- **Return loss**

$$L_{\text{return}}\,[\text{dB}] = -10\log\underbrace{\left(\frac{P_{\text{reflected}}}{P_{\text{incident}}}\right)}_{\text{Reflectivity}}$$

Splice-12

Total Losses in MM Fiber

- **Total loss in multimode fiber is sum of all 7 losses...**

$$L_{\text{intrinsic}} = L_{\text{NA}} + L_{\text{r}} + L_{\text{g}}$$

$$L_{\text{extrinsic}} = L_{\text{lateral}} + L_{\text{logitudinal}} + L_{\text{angular}}$$

$$\boxed{\begin{aligned} L_{\text{MM Total}}[\text{dB}] &= L_{\text{intrinsic}}[\text{dB}] + L_{\text{extrinsic}}[\text{dB}] + L_{\text{reflection}}[\text{dB}] \\ &= L_{\text{NA}}[\text{dB}] + L_{\text{r}}[\text{dB}] + L_{\text{g}}[\text{dB}] + L_{\text{lateral}}[\text{dB}] \\ &\quad + L_{\text{logitudinal}}[\text{dB}] + L_{\text{angular}}[\text{dB}] + L_{\text{reflection}}[\text{dB}] \end{aligned}}$$

Splice-13

Connectors and Splices: Single-Mode Fibers

- **Mode field diameter (MFD) determines sensitivity to misalignment**
- **Coupling efficiency for two single-mode fibers**
  - **MFDs of W_e (emitting fiber) and W_r (receiving fiber)**
  - **Lateral offset d, longitudinal offset s, and angular misalignment θ**

$$\boxed{L_{\text{Total SM}}\,[\text{dB}] = -10\log\left(\underbrace{\frac{16 n_1^2 n_3^2}{(n_1+n_3)^4}}_{\text{reflection}}\frac{4\sigma}{q}e^{-\frac{\rho u}{q}}\right)}$$

n_1 is refractive index of fiber cores (same for both fibers)

n_3 is refractive index of gap medium between fibers

$$\boxed{\begin{gathered}\sigma = \left(\frac{W_r}{W_e}\right)^2, \quad k = \frac{2\pi\ n_3}{\lambda}, \quad \rho = (\mathrm{kW}_e)^2, \\ F = \frac{d}{kW_e^2}, \quad G = \frac{s}{kW_e^2}, \quad q = G^2 + (\sigma+1)^2, \text{ and} \\ \mathrm{u} = (\sigma+1)F^2 + 2\sigma FG\sin\theta + \sigma\left(G^2+\sigma+1\right)\sin^2\theta\end{gathered}}$$

Splices and Connectors: Fiber End Preparation

- **Pits or imperfections scatter light**
- **End preparation techniques**

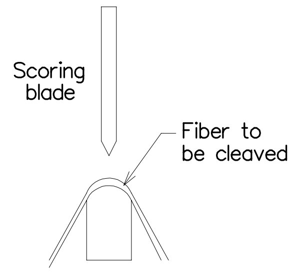
1. *Grinding and polishing technique*

- » **Polish fiber end by hand or machine**
- » **Uses progressively finer abrasives**
- » **Labor and time-intensive**

2. Score-and-break technique (cleaving fiber ends)

- »**Fiber under mild tension and scribed**

Fig. 4.4 p. 103



- »**Tension increased and crack tip propagates across fiber**
- »**If fiber curvature and tension are carefully controlled,**
  - **Crack propagates perpendicular to fiber axis and...**
  - **Creates clean, smooth break**

Splice-15

- Expressions for coupling loss all assume that fiber end is perfect transmitter
- End faces should be parallel to each other (often perpendicular to fiber axis)

Splices and Connectors: Fiber End Preparation (cont.)

- Improper surfaces can have *lip* or *hackle*

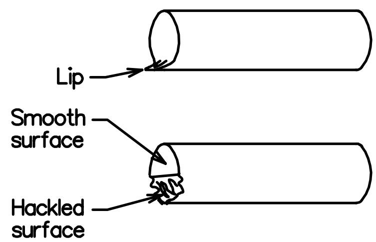


Fig. 4.5
p. 104

- Microscope inspection of fiber end necessary for end inspection
- Tools commercially available
- Takes little time for experienced user

Splice-16

Splices: 1. Fusion Splicing

- **Most popular splice technique**

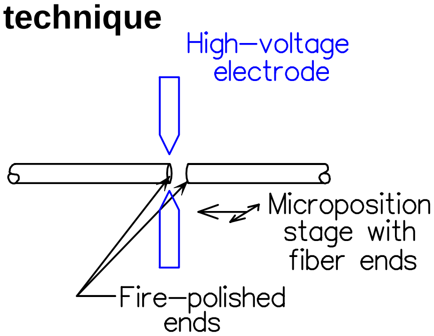


Fig. 4.6 p. 106

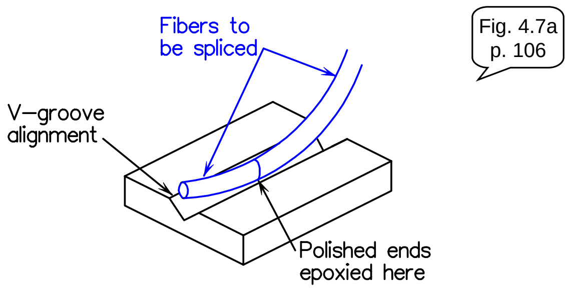
  - **Micro-manipulators bring prepared ends into close alignment (can be automated)**
  - **Ends heated with electric arc until molten; pushed together**
  - **Joint cools, surface tension pulls fibers into alignment**
- **Losses: ~ few tenths of a dB**
- **Primary problem**
  - **Reduced fiber strength near joint (about 60% of initial strength)**
    - **»Use high-strength wrapping around spliced region**

Splice-17

- Strength reduction due to
  - ✳ Development of surface microcracks during handling and
  - ✳ Chemical changes in glass due to heating

Splices: 2. V-groove splice

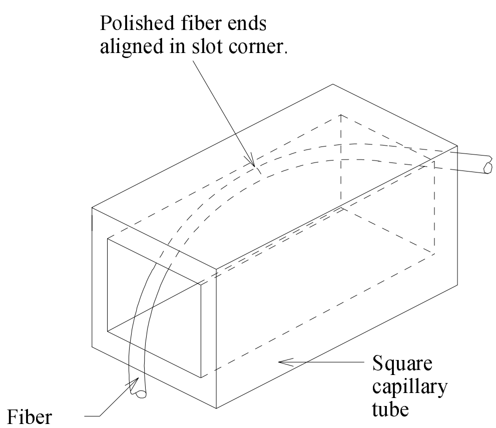
- **V-shaped groove as alignment aid: mechanical alignment**
- **Apply epoxy or cover plate**



- **Grooves in plastic, silicon, ceramic, or metals**
- **Uses outside surface of fiber as reference**
  - **Susceptible to variations in core ellipticity, concentricity, and size**
  - **Unequal diameters cannot be spliced**
- **Fiber ends require preparation before splicing**
- **Losses: few tenths of a dB**

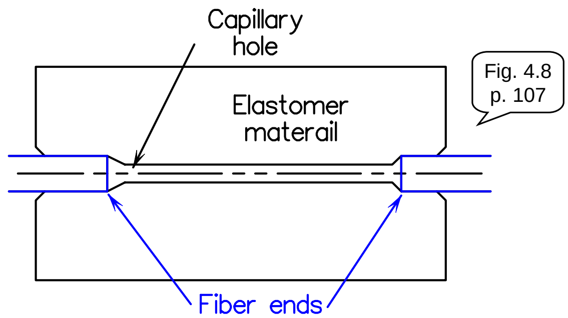
Splice-18

- Variation on this technique, called *loose-tube splice*, uses corner of a rectangular tube as the alignment aid



Splices: 3. Elastic Material Splicing

- Uses elastic material to center fibers



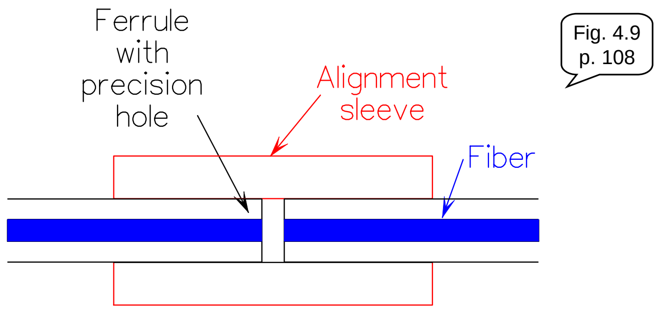
- Self-centering
  - Restoring forces center fiber (with respect to outside surface)
  - Unequal diameters can be aligned
- Fiber ends prepared before insertion
- Drop of epoxy on fiber ends forms splice
- Losses: few tenths of a dB

Connectors

- Allow disconnection and reconnection
- Goal: low insertion-loss connector with reproducible losses
- Most connector designs incorporate fiber into precision alignment aid
  - Aid then plugs into receptacle in connecting piece
- Various environmental factors:
  - Dust levels
  - Pressure differentials
  - Water vapor and water

Connectors: Ferrule-Based Connectors

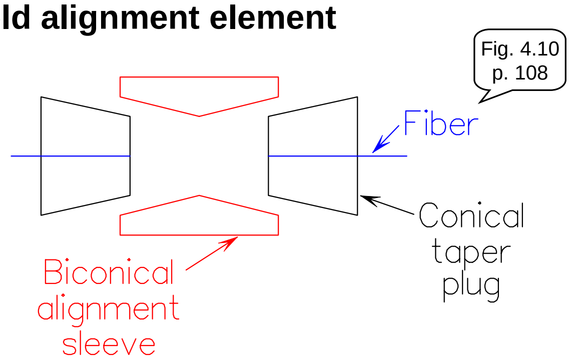
- ***Ferrule***: **precision-drilled hole in cylinder (fiber fits inside hole)**
- **Ferrule fits in *alignment sleeve* to bring the fiber ends into alignment**



- **Main problems:**
  - **Centering fiber hole in ferrule**
  - **Dimensional tolerance on ferrule hole (e.g., 126±1 μm)**
  - **Centering ferrule hole in alignment sleeve**
  - **Making hole slightly larger than fiber**
- **Alignment sleeves commonly made of aluminum, stainless steel, or ceramics**

Connectors: Biconic Plug

- **Injection-mold alignment element**



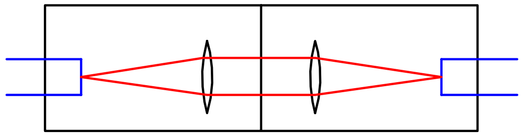
- **Shape is “biconical taper”**
- **Designed to mate with housing such that fiber/plug assembly is self-centering**
- **AT&T patented**
- **Seldom used in new installations**

Splice-22

Connectors: Expanded Beam Connector

- **Microlens inserted at fiber end to *collimate* beam**
  - **Expanded beam has less beam divergence**

Fig. 4.11
p. 109



- **Receiving fiber has similar collimator**
- **Expanded beam reduces requirements on lateral & longitudinal alignments**
  - **Penalty of increasing required angular alignment**
- **Lenses:**
  - **Microlens**
  - **Gradient-index lenses**
  - **Mounted into alignment fixture**
- **Fiber ends prepared prior to insertion**
- **Losses: few tenths of a dB**

- Gradient-index lens
  - ☞ Piece of glass with parabolic variation in *n(r)*
  - ☞ Behaves as a lens but has flat surfaces
  - ☞ Also called *GRIN lens*

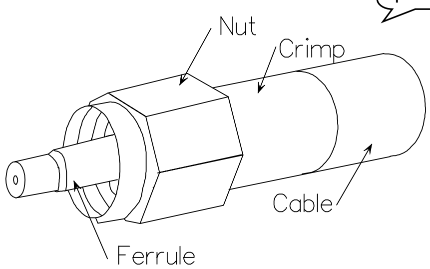
Connectors: Commercial Connectors

- Several connector popular types
- Few standards for connectors
- Patent and proprietary rights
  - Frequently “second-sourced" or cross-licensed
- Typical insertion losses for connectors in the field
  - Few tenths of a dB to a few dB

Commercial Connectors: SMA & Biconic Connectors

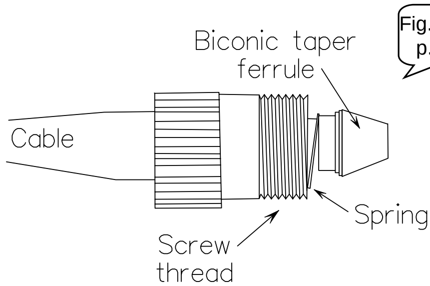
- **SMA connector (left)**
  - **Borrowed from RF field**
  - **Formerly popular connector for multimode fibers**
  - **Ferrule-type connector**

Fig. 4.12a
p. 109



- **Biconic connector (right)**
  - **Developed by AT&T**
  - **Wide use in older single-mode systems**
  - **Supplanted by ST connector**
  - **Uses molded and ground plastic or ceramic plug**

Fig. 4.12b
p. 109

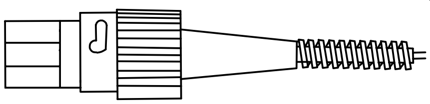


Splice-25

Commercial Connectors: ST & FC Connectors

- ST connector (left)
  - Registered trade-mark (AT&T)
  - Widely used in single-mode systems
  - Also available for multimode systems
  - Features spring-loaded bayonet clip
  - Both score-and-break and grind-and-polish methods used to prepare fiber ends
  - Fairly easy to terminate

Fig. 4.13a p. 110



- FC connector (right)
  - Developed by NTT (Nippon Telephone and Telegraph)
  - Single-mode fibers
  - *D3 connector* is NEC (Nippon Electronics Corporation) clone of FC connector
  - Spring-loaded connector with screw-on nut
  - Metal ferrule aligns fiber

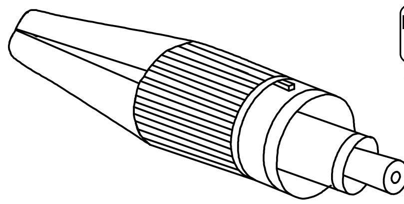
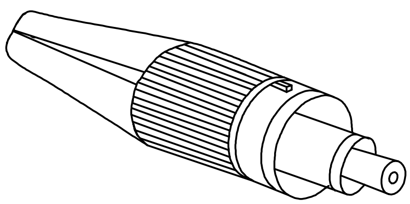


Fig. 4.13b p. 110

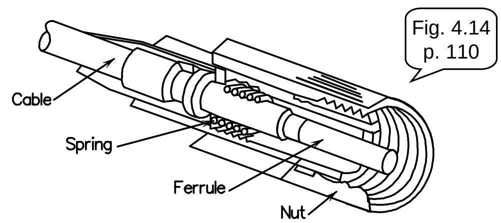
Splice-26

Commercial Connectors: FC/PC & D4 Connectors

- **FC/PC connector**
  - **Offshoot of FC connector**
  - **Pure ceramic ferrule**
    - » **Increased alignment accuracy over metal/ceramic ferrule in FC**
  - **Physical contact to minimize reflections**
  - **Primarily used for long-haul and research instruments**

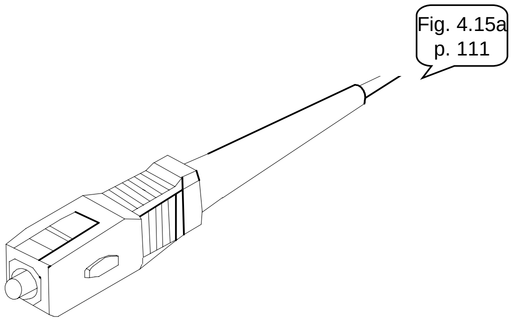


- **D4 connector**
  - **Designed by NEC**
  - **Similar to D3 connector, but smaller**

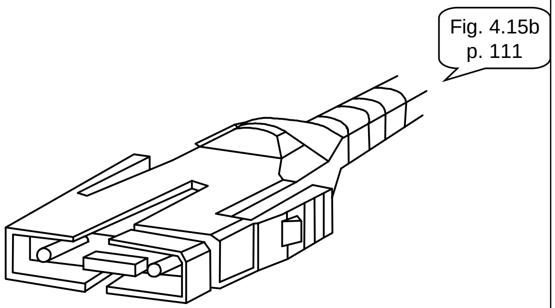


Commercial Connectors: FDDI Connectors

- **SC connector**
  - **Plastic-case connector**
  - **Push-pull configuration**
  - **Ceramic ferrule**
  - **Increasingly popular in networks**



- **FDDI connector**
  - **Dual-fiber connector**
  - **FDDI standard**
  - **Use in FDDI data links**
  - **Used for attachment to stations on link**

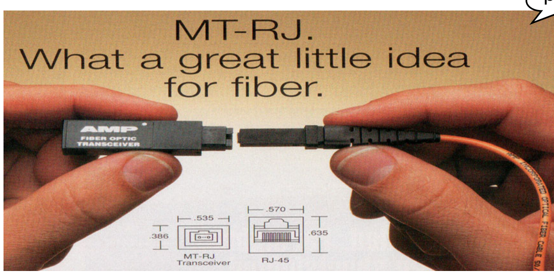


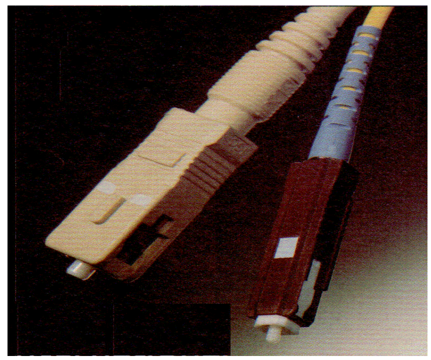
Splice-28

Miniature RJ and MU Connectors

- New connectors
- Network applications
- Compatible with network wall plugs
- Small "footprint"
- RJ (left)
- SC vs MU (right)

Fig. 4.16
p. 111





ST-Connector Spec Sheets

- ST Connector specs
- See course Website

Splice and Connector: Loss Measurement

- **Measured losses depend on many variables**
  - **Optical power launch conditions**
    - **Excite all modes in MM fiber**
      - **Use long pigtail**
      - **Equilibrium mode simulator: short fiber wrapped in serpentine path**
  - **Source type**
  - **Characteristics of fiber on either side of joint**
- **Experimental setup**
  - **Measure power P_1 and P_2 at the input and output of connector**

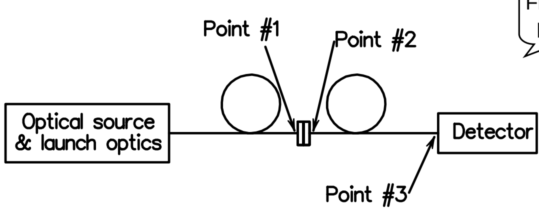


Fig. 4.17 p. 112

$$L_{\text{splice}}\,[\text{dB}] = -10\log\left(P_2/P_1\right)$$

insertion loss

Splice-31

- Losses measured are very susceptible to mode excitation
  - ☞ Equal mode excitation desired
  - ☞ Can use
    - ✳ Long fiber before connector/splice
    - ✳ Shorter fiber wrapped in serpentine path
- Multimode fibers can introduce loss effects
  - ☞ Due to mode coupling and connector/splice effects

Couplers

- Couplers
  - Split power into two or more fibers
  - Combine optical power
  - Split light according to polarization
  - Optical switches: switch light between output fibers
- Usually each output equally shares signal
  - Possible to vary *coupling fraction*
- Losses
  - *Splitting loss*: $\boxed{L_{\mathrm{Splitting}}\,[\mathrm{dB}] = -10\log(1/N) = +10\log(N)}$
  - *Excess losses:* extra losses
  - *Insertion loss:* $\boxed{L_{\mathrm{Insertion}}\,[\mathrm{dB}] = L_{\mathrm{Splitting}}\,[\mathrm{dB}] + L_{\mathrm{Excess}}\,[\mathrm{dB}]}$
  - Splitting matrix:

Losses		Output port	
		A	B
Input port	1	3.5 dB	3.5 dB
	2	3.5 dB	3,5 dB

Coupler Functions

- ***Splitter***
  - **Splits/divides power**
  - **Standard splits for 2x2: 50:50, 90:10, 99:1**
  - **Other custom ratios**
- ***Polarizing splitter***
  - **Splits signals into two outputs**
  - **Output polarizations ortho-gonal**
  - **Single-mode fibers**

- ***Combiner***
  - **Combines input channels into one**
  - **Coherent combination possible with SM fiber**
  - **Many (*not* all) passive devices are reciprocal**
    - **»Splitter sometimes used as combiner (but has splitting loss)**

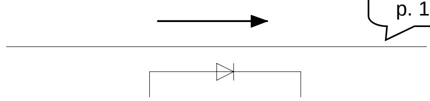
Fig. 4.18a & b
p. 114

Splice-33

Coupler Functions (cont.)

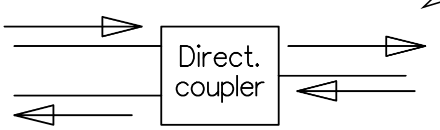
- ***Monitor*:**
  - **Couples little light (e.g., 1%) into monitor port**

Fig. 4.18c p. 114



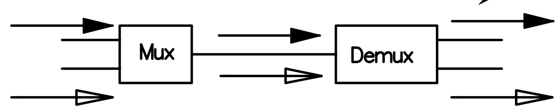
- ***Directional coupler* (or *circulator*) :**
  - **Nonreciprocal device**
  - **Isolates one input from one output**

Fig. 4.19a p. 115



- **Multiplexer (wavelength multiplexer):**
  - **Combiner**
  - **Joins two or more signals at different wavelengths**
- **Demultiplexer (wavelength demultiplexer):**
  - **Splits signals according to wavelength**

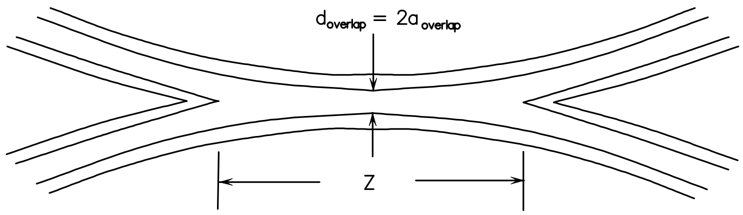
Fig. 4.19b p. 115



Couplers: 1. Fused Coupler

- **Also called *biconical taper coupler***
- **Light couples into other fibers through merged core**

Fig. 4.21 p. 116



$$\Delta a = \frac{d_{\text{overlap}} - 2a}{2}$$

- **Control $\Delta a/a$ and Z**
  - **Ex., make 50:50 coupler or 1500/1300 splitter**

Power coupling:

$$\xi = \sqrt{F^2 \sin^2\left(\frac{CZ}{F}\right)}$$

where

$$F = \frac{1}{\sqrt{1 + \left(\frac{234a^2}{\lambda^3}\right)\left(\frac{\Delta a}{a}\right)^2}}; \qquad C = \frac{21\lambda^{5/2}}{a^{7/2}}$$

Splice-35

Fused Coupler (cont)

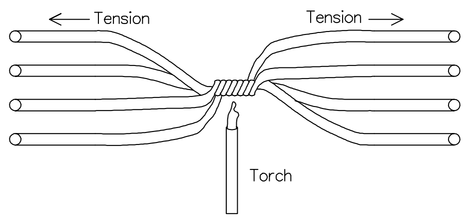


Fig. 4.20
p. 116

- **Coupling fraction controlled by amount of tension and time of heating.**
  - **Surprisingly, equal coupling can be achieved for all fibers with very low crosstalk and low insertion loss**
  - **>100 fibers formed into star coupler**

Couplers: 2. Planar Lightwave Circuits (PLCs)

- **Optical waveguides (rectangular) deposited in silicon**
- **Used to make passive and hybrid optical devices**

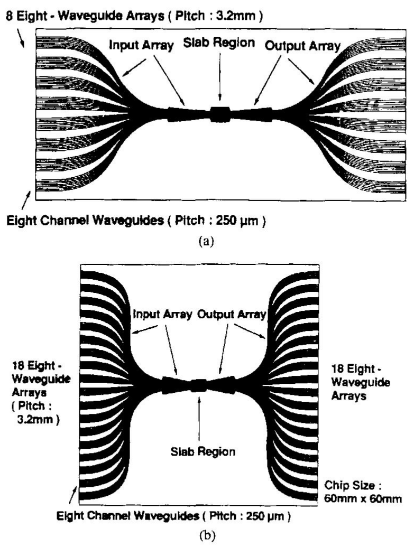


Fig. 1. Layouts of integrated-optic (a) 64 × 64 and (b) 144 × 144 star coupler chips.

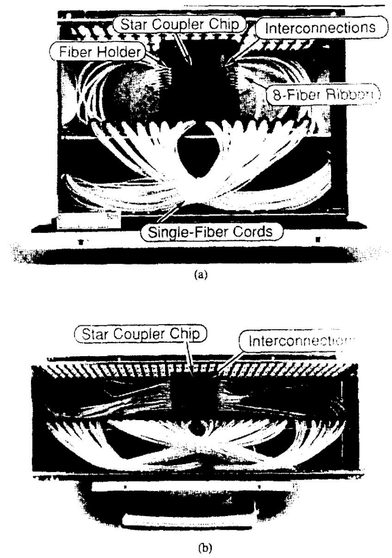


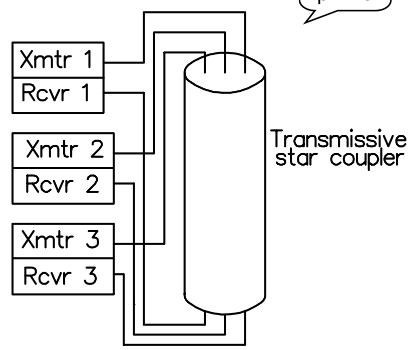
Fig. 3. Photographs of packaged (a) 64 × 64 and (b) 144 × 144 star coupler modules in bookshelf-type unit.

Splice-37

Couplers: 3. Mode-Mixing Rods

- Glass rod
  - Few mm diameter
  - Graded-index profile
  - Length allows input light to fully expand
  - Output end uniformly excited
- Concept works in transmissive configuration
  - Make *reflective* system by
    - » Cutting in half,
    - » Adding reflecting surface,
    - » Moving outputs to same end as inputs

Fig. 4.23
p. 119



Splice-38

Couplers: Typical Specifications

- Losses
  - Desired *splitting loss*
    - » $L_{split}[dB] = -10\log(1/N) = 10\log(N)$
  - Undesired *excess loss*
    - »Typical excess losses: ~ 0.5 dB
- SM and MM couplers available
- See course website for sample spec sheets
- Couplers & WDM (E-Tek Dynamics) (WWW)

Splice-39

Couplers: Matrix Formulation

- **Can use matrix notation and phasors to represent SM coupler**

$$\begin{bmatrix} \tilde{E}_{\text{out upper}} \\ \tilde{E}_{\text{out lower}} \end{bmatrix} = \tilde{\mathbf{S}} \begin{bmatrix} \tilde{E}_{\text{in upper}} \\ \tilde{E}_{\text{in lower}} \end{bmatrix}$$

$$\tilde{\mathbf{S}} = \begin{bmatrix} \sqrt{1-\xi} & \sqrt{\xi}e^{j\pi/2} \\ \sqrt{\xi}e^{j\pi/2} & \sqrt{1-\xi} \end{bmatrix} = \begin{bmatrix} \sqrt{1-\xi} & j\sqrt{\xi} \\ j\sqrt{\xi} & \sqrt{1-\xi} \end{bmatrix}$$

- **Crossing inputs→outputs have a π/2 phase shift relative to the noncrossing waves!!**

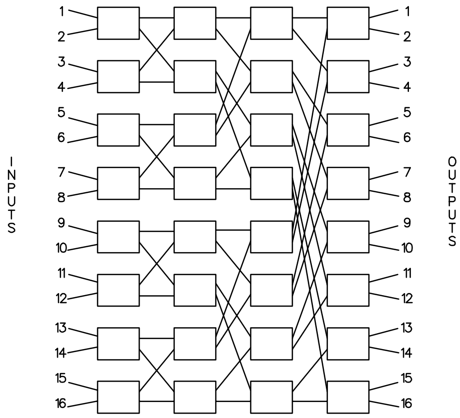
$$\tilde{\mathbf{S}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & e^{j\pi/2} \\ e^{j\pi/2} & 1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \quad \text{for 50:50 coupler}$$

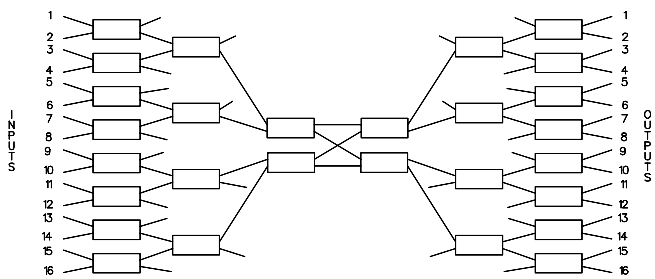
Splice-40

Cascaded Couplers

- **Can cascade 2x2 couplers to build *N*x*N* couplers**

Fig. 4.24
p. 120





Splice-41

Splices, Connectors and Couplers: Summary

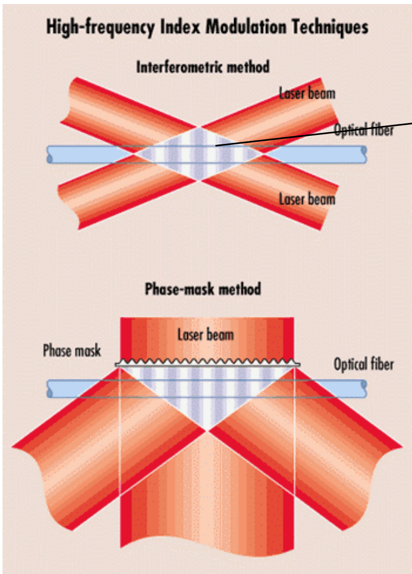
- **Splices and connectors**
  - **Losses depend on...**
    - » **Fiber geometry** (core ellipticity, core-cladding concentricity, area mismatches, etc.)
    - » **Characteristics of fiber** (NA, index profile)
    - » **Mechanical alignment** (lateral and longi-tudinal displacement, angular misalignment)
    - » **Power distribution in fiber** (excitation conditions or mode conversion effects)
    - » **Fiber end-face quality** (scratches, presence of lips or hackles, parallelness of end faces)
  - **Commercial connectors and splicing have acceptable losses** (<1 dB)
- **Couplers**
  - **Combine and separate light**
  - **Primary parameters**
    - » **Insertion loss**
    - » **Splitting loss of coupler**

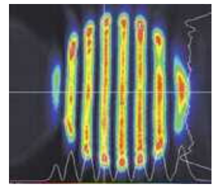
Splice-42

Fiber Grating Devices

- Goal: inline optical filters with low insertion loss
- Applications
  - Add/drop filters for multiwavelength systems
  - Reflectors for amplifiers and fiber lasers
  - Reflectors for external-cavity lasers
  - Dispersion compensating devices
- Physical effect
  - High intensity UV can change *n* of glass (permanently)
  - Expose fiber to interference pattern to write “grating” in fiber core
    - » Use side exposure through “phase mask”
  - Transmission/reflection spectral properties depend on grating period and amplitude

Writing Bragg Gratings





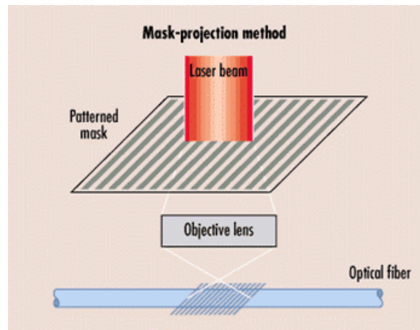
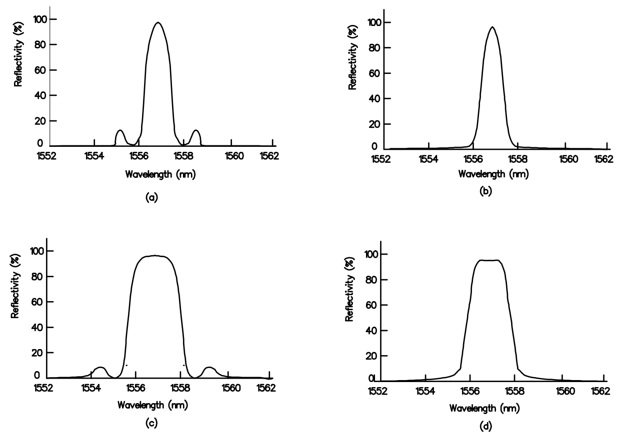


Figure 1. Interferometric, phase-mask, and mask-projection methods are three alternate ways to produce the required high-frequency index modulation necessary for fiber Bragg gratings.

Grating Designs

- **Spectral distribution of reflectivity**
  - **(a) Period grating, equal amplitude**
    - **Peaked response, sidelobes**
  - **(b) Periodic grating, apodized amplitude**
    - **Peaked response, reduced sidelobes**
  - **(c) "Chirped" period, equal amplitude**
    - **Flat response, sidelobes**
  - **(d) Chirped period, apodized amplitude**
    - **Flat response, reduced sidelobes**

Fig. 4.25
p. 122

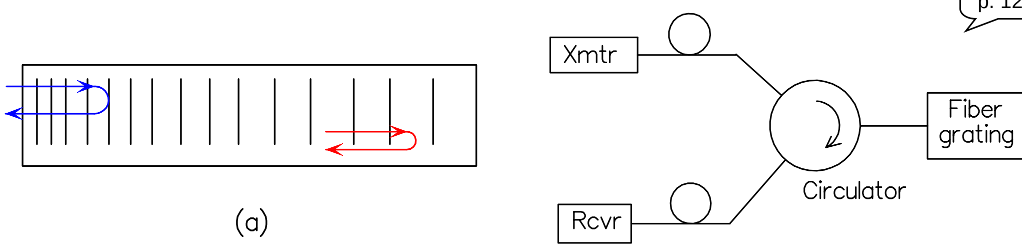


Splice-45

Fiber Gratings: Dispersion Compensation

- **Aperiodic grating**
- **Short-λ reflect in regions of high spatial periodicity**
- **Design grating to “reverse” pulse-stretching effects of GVD dispersion in SM fibers**

Fig. 4.26
p. 123



(a) (b)

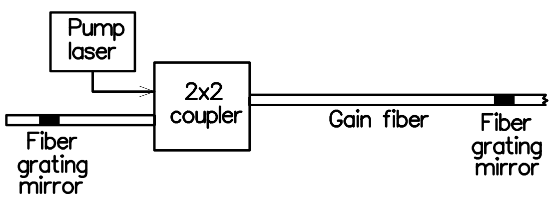
Circulator (E-Tek Dynamics) (WWW)
Dispersion compensators (E-Tek Dynamics) (WWW)

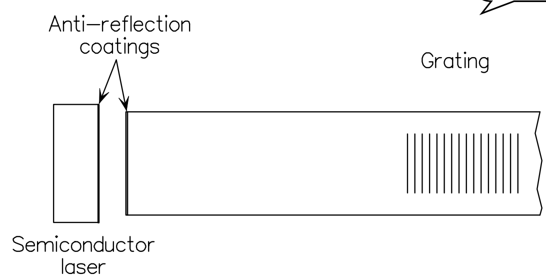
Splice-46

Fiber Gratings: Laser Reflectors

- **High reflectivity at desired wavelength**
  - **Left - fiber laser with grating mirrors**
  - **Right - external cavity laser (long resonator length ensures small $\Delta\nu$)**

Fig. 4.27
p. 124





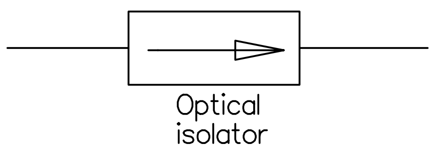
Fiber Grating Spec Sheet

- See course website

Splice-48

Optical Isolators

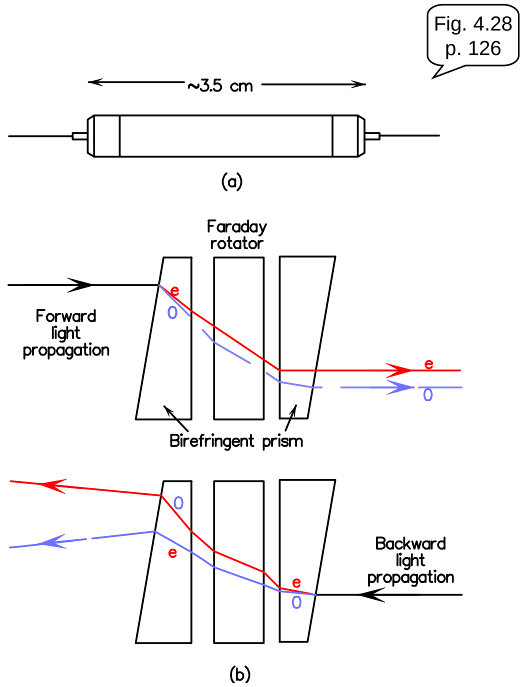
- Ensure one-way light flow
- Return loss
  - –30 dB nominal
  - –60 dB premium device
- Applications
  - Isolate single-frequency lasers
  - Isolate optical amplifiers



Splice-49

Optical Isolators: Principles
Polarization-Independent Isolator

- Nonreciprocal device
- Collimating and focusing lenses not shown
- Birefringent wedge
  - Light polarized along one axis has one velocity
  - Light polarized along other axis has different velocity
  - Refraction angle at interface is different for two polarizations
- Faraday rotator
  - Magnetic field present
  - Light polarization is rotated; amount is dependent on material, magnetic field strength, length of propagation



Splice-50

Optical Isolators: Principles
Polarization-Dependent Isolator

- **Wedges replaced by polarizers**
- **Forward:**
  - **Align input polarization with input polarizer** **(collimating and focussing lenses not shown)**
  - **Polarization axis rotated 45˚ (clockwise as seen from input) by rotator**
  - **Output aligns with output polarizer**
- **Backward:**
  - **Back light is polarized by rear polarizer at 45° from vertical**
  - **Polarization rotates 45° by rotator to horizontal orientation**
  - **Blocked by input polarizer** **(severe attenuation)**

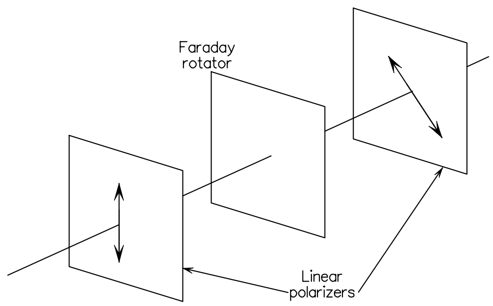


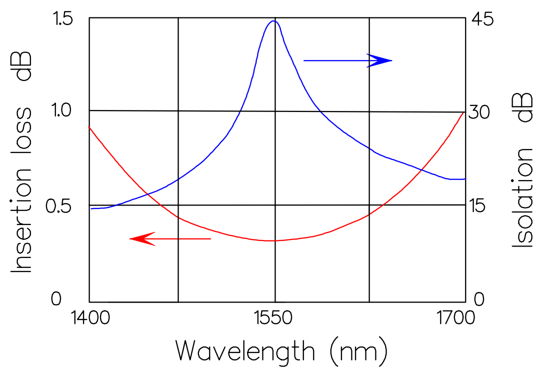
Fig. 4.29 p. 127

Optical Isolators: Specifications

Fig. 4.30
p. 128

- **Insertion Loss**

$$L_{\text{insertion}}\ [\text{dB}] = -10\log\underbrace{\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)}_{\substack{\text{Forward}\\\text{transmissivity}}}$$



- **Isolation**

$$L_{\text{isolation}}\ [\text{dB}] = -10\log\underbrace{\left(\frac{P_{\text{back, out}}}{P_{\text{back, in}}}\right)}_{\substack{\text{Reverse}\\\text{transmissivity}}}$$

- **Return loss**

$$L_{\text{return}}\ [\text{dB}] = -10\log\underbrace{\left(\frac{P_{\text{reflected}}}{P_{\text{in}}}\right)}_{\text{Reflectivity}}$$

Splice-52

Optical Isolators: Specifications

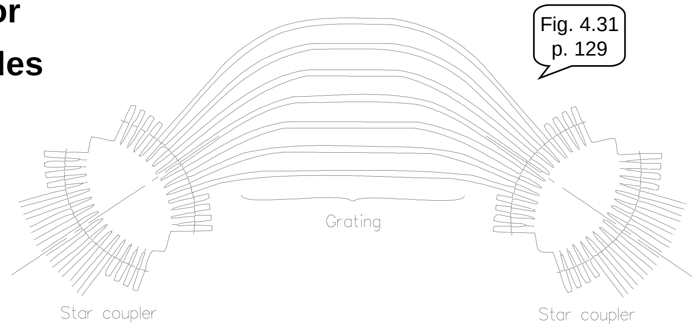
- Other specifications
  - Polarization-dependent loss (PDL): Maximum variation of insertion loss as input polarization state is changes over 180° for a polarization-independent device
  - Polarization mode dispersion (PMD): Difference in propagation times through isolator when input polarization is rotated through 180°
  - Power handling capacity: maximum optical power without any danger of injuring coatings or components

- See website for isolator specifications

Arrayed-Waveguide Grating (AWG) Couplers

- **Device that multiplexes and demultiplexes *N* signals at multiple wavelengths without a splitting loss**
- **Consists of…**
  - **Input waveguide array**
  - **Input distributor**
  - **Waveguide array** **(each pathlength Δl shorter than previous)**
  - **Output distributor**
  - **Output waveguides**

Fig. 4.31
p. 129

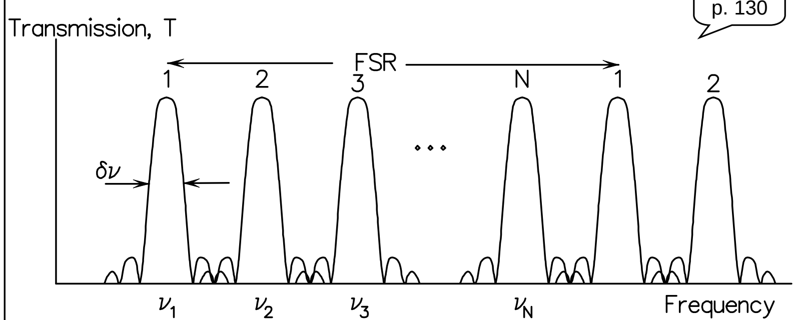


Splice-54

AWG Couplers

- **Spectral transmission**
- **N separate responses**
- $\delta\nu$ **= width of response for each channel**
- **Free spectral range = total spectrum covered = *N*** $\delta\nu$
- **Design to maximize *N*, FSR; choose *dl* for desired** λ_1, λ_2, λ_3,... λ_N

Fig. 4.32
p. 130



$$\mathrm{FSR} = \frac{c}{n\Delta l} = \frac{\nu}{q}$$

$$q = \frac{n\Delta l}{\lambda} = \frac{\nu}{\mathrm{FSR}} \qquad (q \sim 60)$$

$$\delta\nu = \frac{\mathrm{FSR}}{N} = \frac{\nu}{qN} = \frac{c}{q\lambda N}$$

$$N = \frac{\mathrm{FSR}}{\delta\nu} = \frac{\nu}{q\,\delta\nu} = \frac{c}{q\lambda\,\delta\nu}$$

Splice-55

AWG Couplers: MUX and DEMUX

- **Physical layout; functional diagram (note reversal of output ports)**
- **One signal on each port...**
  - **– λ_1 in on input #1 comes out output #1**
  - **– λ_2 in on input #2 comes out output #2**
  - **– λ_N in on input #N comes out output #N**

Fig. 4.33a p. 132

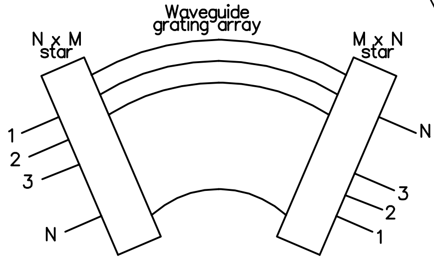
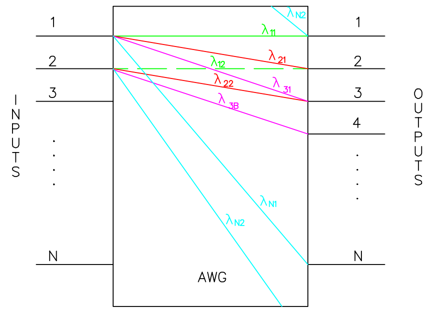


Fig. 4.33b p. 132



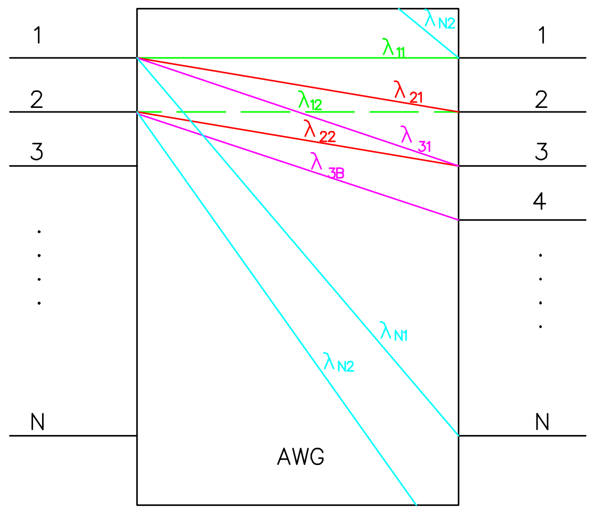
AWG Couplers: MUX and DEMUX (cont)

- **Multiple signals on one input...**
  - **– λ_1 in on input #1 comes out #1**
  - **– λ_2 in on input #1 comes out #2**
  - **– λ_N in on input #1 comes out #N**

  - **– λ_1 in on input #2 comes out #2**
  - **– λ_2 in on input #2 comes out #3**
  - **– λ_3 in on input #2 comes out #4**
  - **– λ_N in on input #1 comes out # N+1 = #1 (grating "wrap-around" property)**

  - **– All *N* wavelengths in any input port will appear at outputs; one wavelength at each output ("wavelength demultiplexing")**

Fig. 4.33b p. 132



Note: Edge ports have higher losses; arrange so light comes in on a center port

AWG Couplers: MUX and DEMUX (cont)

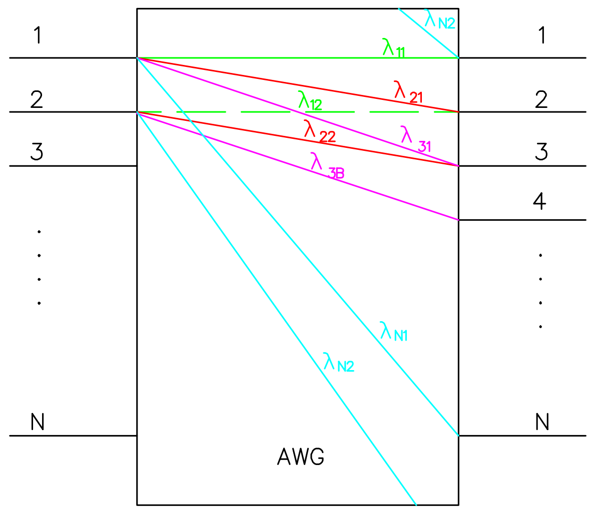
- **Device is reciprocal**
- **Run "backwards"**
- **λ_1 applied at "output" 1 appears at "input" 1**
- **λ_2 applied at "output" 2 appears at "input" 1**
- **λ_1 applied at "output" 1 appears at "input" 1**

- **All wavelengths appear at "input" port 1**

- **"Wavelength multiplexing"**

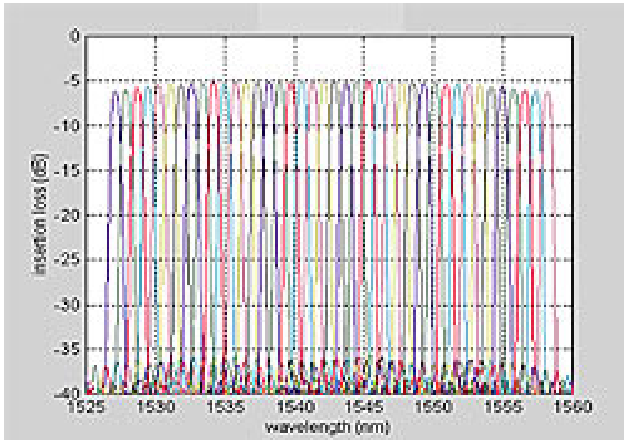
Note: Edge ports have higher losses; arrange so light comes out of center port

Fig. 4.33b p. 132



AWG Couplers: MUX and DEMUX (cont)

- **Measured Response**

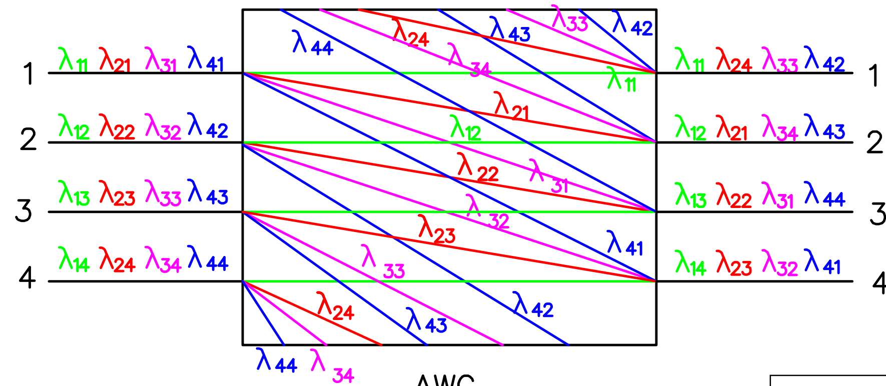


- **AWG (Microsystems)**
- **AWG (Lucent)**

AWG Couplers: NxN Wavelength Routing

- **Use input wavelength to decide which output receives signal**

Fig. 4.34
p. 133



AWG
(a)

- ***N* wavelengths produce *N*^{2} possibilities**

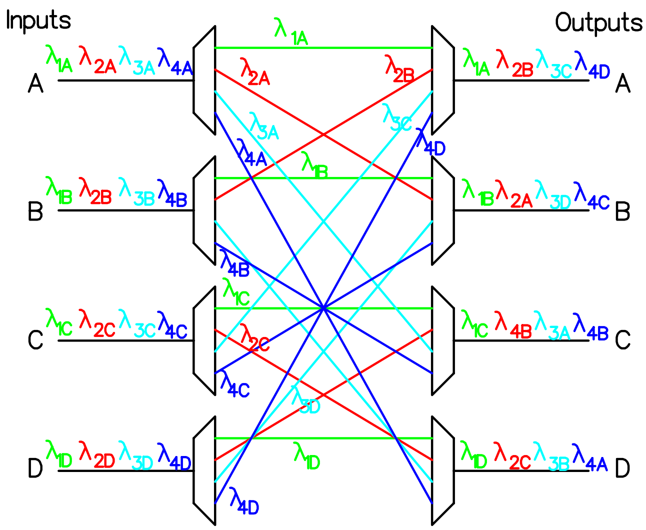
INPUTS	OUTPUTS 1	2	3	4
1	λ_{11}	λ_{21}	λ_{31}	λ_{41}
2	λ_{42}	λ_{12}	λ_{22}	λ_{32}
3	λ_{33}	λ_{43}	λ_{13}	λ_{22}
4	λ_{24}	λ_{34}	λ_{44}	λ_{14}

(b)

Splice-60

Wavelength Routing Concept

- **Output exits determined by wavelength and input port**



(a)

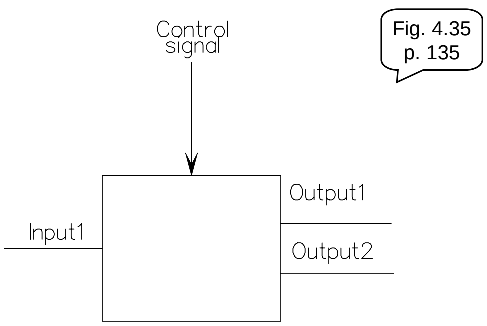
INPUT \ OUTPUT	A	B	C	D
A	λ	λ	λ	λ
B	λ	λ	λ	λ
C	λ	λ	λ	λ
D	λ	λ	λ	λ

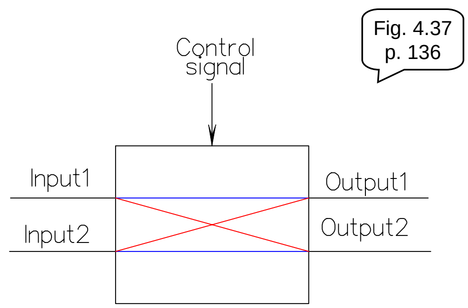
(b)

Splice-61

Optical Switches

- **Switch optical path under electronic or optical control signal**
- **Simplest is 1 input and two outputs (left)**
- **Most common is 2x2 crossconnect switch (right)**
  - **State #1: signals pass straight through ("bar state")**
  - **State #2: signals cross ("cross state")**
- **NxN switch can connect any input to any output**
- **Switch properties: speed, crosstalk, insertion loss**



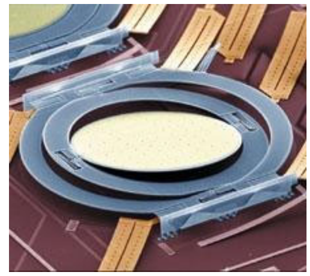


Splice-62

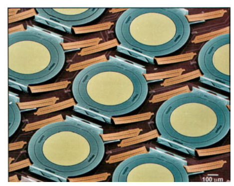
Types of Switches

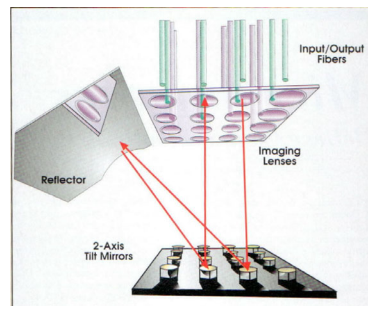
Fig. 4.36
p. 134

- **Mechanical**
  - **Deflect or move component**
  - **Slow (ms)**
- **Thermo-optic**
  - **Change refractive index by localized heating**
  - **Slow (~ms)**
- **Electro-optic**
  - **Change index of refraction by applied electric field**
  - **Fast (<ps)**



MEMS (micro-electro-mechanical system) mirror used to reflect light into different output ports





Splice-63

Electro-optic Switches

- **Fast switches**

(a) Directional-coupler switch

(b) Reversed delta-beta coupler

(c) Balanced-bridge interferometric switch

(d) Intersecting waveguide switch

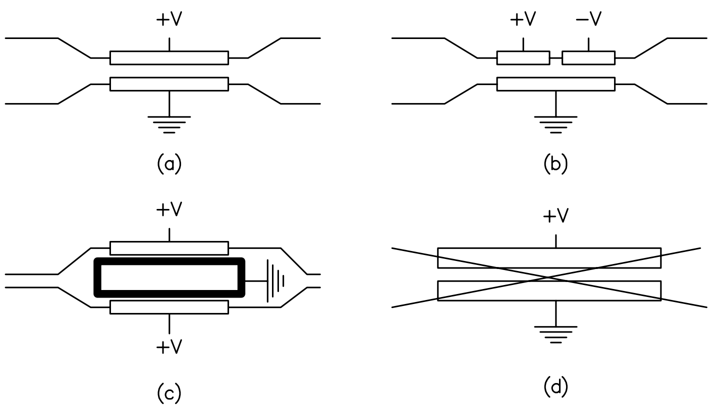


Fig. 4.38
p. 136

Gate Switches

- **Consists of splitters, gating elements (amplifiers or absorbers), combiners**
- **Problems with losses for large *N* (8x8 switch with amplifiers has been demonstrated)**
- **Can be fabricated in integrated-optic form**

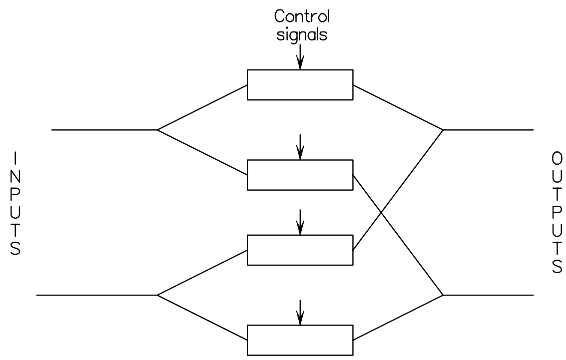


Fig. 4.39
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Splice-65

Optical Switching Vocabulary

- **“Relational devices” – Data flows through switches; switch setting is oblivious to data content (“data transparency”)**
- **“Logic devices” – Switch setting depends on data content**
  - **Ex., switch setting depends on destination address in data packet**
- **Switches (E-Tek Dynamics) (WWW)**

More on switches forthcoming
(Under Construction)

Summary

- **Use splices for permanent connection; connectors for demountable connection**
  - **Losses depend on fiber properties (intrinsic losses) and fiber alignment (extrinsic losses)**
  - **Losses ~0.1s dB**

- **Fiber components allow manipulation of light power (amplitude, phase, polarization, etc.)**
  - **Splitters, combiners, circulators (directional couplers), multiplexers and demultiplexers, switches, polarization components (splitters, combiners, isolators)**
  - **Filters (Bragg gratings, stacked dielectric layers, Fabry-Perot mirrors)**